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Short-term influence of anaerobically-digested and conventional swine manure, and N fertilizer on organic C and N, and available nutrients in two contrasting soils

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ABSTRACT

A three-year (2006-2008) field experiment was conducted at Swift Current and Star City in Saskatchewan to determine the short-term influence of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and N fertilizer on total organic C (TOC), total organic N (TON), light fraction organic C (LFOC), light fraction organic N (LFON) and pH in the 0 - 7.5 and 7.5 - 15 cm soil layers, and ammonium-N, nitrate-N, extractable P, exchangeable K and sulphate-S in the 0 - 15, 15 - 30, 30 - 60, 60 - 90 and 90 - 120 cm soil layers. Treatments included spring and autumn applications of CTSM and ADSM at a 1x rate (10,000 and 7150 L·ha^{-1}, respectively) applied each year, a 3x rate (30,000 and 21,450 L·ha^{-1}, respectively) applied once at the beginning of the experiment, plus a treatment receiving commercial fertilizer (UAN at 60 kg·N·ha^{-1}·yr^{-1}) and a zero-N control. There was no effect of swine manure rate, type and application time on soil pH. Mass of TOC and TON in the 15 cm soil layer increased significantly with swine manure application compared to the control, mainly at the Swift Current site, with greater increases from 3x rate than 1x rate (by 2.21 Mg·C·ha^{-1} and 0.167 Mg·N·ha^{-1}). Compared to the control, mass of LFOC and LFON in the 15 cm soil layer increased with swine manure application at both sites, with greater increases from 3x rate than 1x rate (by 287 kg·C·ha^{-1} and 26 kg·N·ha^{-1} at Star City, and by 194 kg·C·ha^{-1} and 19 kg·N·ha^{-1} at Swift Current). Mass of TOC and TON in soil layer was tended to be greater with ADSM than CTSM, but mass of LFOC and LFON in soil was greater with CTSM than ADSM. Mass of TOC, TON, LFOC and LFON in soil also increased with annual N fertilizer application compared to the control (by 3.2 Mg·C·ha^{-1} for TOC, 0.195 Mg·N·ha^{-1} for TON, 708 kg·C·ha^{-1} for LFOC and 45 kg·N·ha^{-1} for LFON). In conclusion, our findings suggest that the quantity and quality of organic C and N in soil can be affected by swine manure rate and type, and N fertilization even after three years, most likely by influencing inputs of C and N through crop residue, and improve soil quality.

Keywords: Anaerobic Digestion; Available N; P, K and S; Organic C and N; Soil; Swine Manure

1. INTRODUCTION

Of the approximately 30 million hogs marketed in Canada, nearly one-half of that industry is located in the Canadian prairie region, and approximately 90% of intensive livestock operations (ILOs) store manure in liquid form in a holding tank or lagoon until it can be land-applied. Land application of liquid swine manure (LSM) is an effective source of nutrients for crop production [1-3]. Economically feasible, environmentally friendly, and socially acceptable management of LSM from ILOs is a key element for the future viability of this industry. In LSM, there is usually less than 2% solid material [4] and most of the nutrients are in plant-available inorganic form. Thus, LSM can potentially increase soil organic C (SOC) mainly by supplying nutrients to crops [5,6] and increasing above and below ground plant biomass thereby adding organic matter to the soil. In the Prairie Provinces of Canada, previous research has documented the agronomic benefits of LSM application on enhancing crop yields [1]. Increased soil fertility is an important benefit of LSM application that substantially increases the concentration of N, P, K and micronutrients in soil [1,3].

Anaerobic digestion is a promising technology that may reduce greenhouse gas (GHG, CH_4 and N_2O) emissions by utilizing the biogas produced during digestion to displace fossil fuels and by reducing emissions during lagoon storage. The effects of land-applied anaerobically digested swine manure (ADSM) versus conventionally treated swine manure (CTSM) or N fertilizer on crop yields and GHG emissions in the Canadian prairies are presented in our previous report [7]. However, the research information on the impact of ADSM versus CTSM or N fertilizer on soil biochemical and chemical properties is lacking in the Canadian prairies, especially in the Parkland region. The objective of this study was to compare relative effects of land-applied ADSM, CTSM, or N fertilizer on quantity and quality of soil organic C and N (TOC, TON, LFOC and LFON), and some soil chemical properties (pH, ammonium-N, nitrate-N, extractable P, exchangeable K and sulphate-S).

2. MATERIALS AND METHODS

A field experiment was conducted over three years from 2006 to 2008 at two field sites in Saskatchewan [Star City (Dark Gray Luvisol soil) and Swift Current (Brown Chernozem soil)], having contrasting soil and climatic conditions. Precipitation in the growing season (May, June, July and August) at the two sites from 2006 to 2008, and long-term (30-year) average of precipitation in May to August at the nearest Environment Canada Meteorological Station (AAFC Melfort and AAFC Swift Current) are presented in **Table 1**. Precipitation in the 2006 growing season was slightly below average at both sites. In 2007, the growing season precipitation was much below long-term average at Swift Current (with particularly limited precipitation in July), but was slightly above average at Star City. In 2008, the growing season precipitation was much higher than average (especially in June) at Swift Current, but much below average (especially in May during seeding) at Star City. Treatments included autumn and spring applications of CTSM and ADSM at a 1x rate (10,000 and 7150 $L \cdot ha^{-1}$ respectively) applied each year, and a 3x rate (30,000 and 21,450 $L \cdot ha^{-1}$ respectively) applied once at the beginning of the study. A treatment receiving commercial fertilizer urea-ammonium nitrate (UAN) solution and a check (no N) were also included. Eleven treatments (**Table 2**) were arranged in a randomized complete block design with four replications. Liquid swine manures were applied by the Prairie Agricultural Machinery Institute (PAMI) using a customized applicator, which injected the material to 10 cm. All plots were seeded to barley (*Hordeum vulgare* L.) in each of the three years, and harvested for seed and straw yield, and total N uptake. In the autumn of 2008, soil in each plot was sampled to 0 - 7.5, 7.5 - 15 and 15 - 20 cm depths for TOC, TON, LFOC, LFON and pH, and to 0 - 15, 15 - 30, 30 - 60 and 60 - 90 cm depths for ammonium-N, nitrate-N, extractable P, exchangeable K and sulphate-S.

For TOC, TON, LFOC, LFON and pH, soil cores at 10 locations in each plot were collected using a 2.4 cm diameter coring tube. Bulk density of soil was determined by the core method using soil weight and core volume [8]. The soil samples were air dried at room temperature after removing coarse roots and easily detectable crop

Table 1. Monthly cumulative precipitation in the growing season during 2006, 2007 and 2008 at Star City and Swift Current, Saskatchewan.

Location/Year	Precipitation (mm)				
	May	June	July	August	Total
Star City					
2006	63	73	39	46	221
2007	71	119	47	40	277
2008	6	32	117	22	177
30-year mean	46	66	76	57	245
Swift Current					
2006	35	96	31	21	183
2007	26	48	10	19	103
2008	27	152	64	69	312
30-year mean	50	66	52	40	208

Table 2. List of treatments and the corresponding total amount of N applied and input of C from crop residue returned and land-applied liquid swine manure (LSM) during a three-year (2006-2008) field study at Star City and Swift Current, Saskatchewan.

Time of application	Product applied[z]	Application rate of LSM or N fertilizer	Total amount of N applied in 3 years ($kg·N·ha^{-1}$)	Input of C from crop residue plus LSM in 3 years at Star City ($kg·C·ha^{-1}$)	Input of C from crop residue plus LSM in 3 years at Swift Current ($kg·C·ha^{-1}$)
	Control	No manure or N fert	0	4037	3710
Autumn	ADSM-3x	21,450 $L·ha^{-1}$	214	6665	5753
	ADSM-1x	7150 $L·ha^{-1}$	205	6446	4719
	CTSM-3x	30,000 $L·ha^{-1}$	403	7603	5919
	CTSM-1x	10,000 $L·ha^{-1}$	360	8765	4872
Spring	ADSM-3x	21,450 $L·ha^{-1}$	257	6745	5270
	ADSM-1x	7150 $L·ha^{-1}$	255	7601	4444
	CTSM-3x	30,000 $L·ha^{-1}$	343	7405	5701
	CTSM-1x	10,000 $L·ha^{-1}$	326	7906	5210
	UAN	60 $kg·N·ha^{-1}$	180	6158	5278

[z]ADSM = anaerobically digested swine manure, CTSM = conventionally treated swine manure, UAN = urea ammonium nitrate (liquid), 3x = once in 3 years, 1x = annual application.

residues, and ground to pass a 2-mm sieve. Sub-samples were pulverized in a vibrating-ball mill (Retsch, Type MM2, Brinkman Instruments Co., Toronto, Ontario) for determination of TOC, TON, LFOC and LFON in soil. Soil samples used for organic C and N analyses were tested for the presence of inorganic C (carbonates) using dilute HCl, and none was detected in any soil sample. Therefore, C in soil associated with each fraction was considered to be of organic origin. Total organic C in soil was measured by Dumas combustion using a Carlo Erba instrument (Model NA 1500, Carlo Erba Strumentazione, Italy), and Technicon Industrial Systems [9] method was used to determine TON in the soil. Light fraction organic matter (LFOM) was separated using a NaI solution of 1.7 $Mg·m^{-3}$ specific gravity, as described by Janzen *et al.* [10] and modified by Izaurralde *et al.* [11]. The C and N in LFOM (LFOC, LFON) were measured by Dumas combustion.

Soil samples (ground to pass a 2-mm sieve) taken for organic C and N from the 0 - 15 cm layer were also monitored for pH in 0.01 M $CaCl_2$ solution with a pH meter. For other chemical properties, soil cores (using a 4 cm diameter coring tube) were collected at 4 locations in each plot from the 0 - 15, 15 - 30, 30 - 60, 60 - 90 and 90 - 120 cm layers. The bulk density of each depth was calculated using soil weight and core volume [8]. The soil samples were air dried at room temperature, ground to pass a 2-mm sieve, and analyzed for ammonium-N [12] and nitrate-N [13] by extracting soil in a 1:5 soil: 2M KCl solution; extractable P [9] by extracting soil in Kelowna extract, exchangeable K [14] and sulphate-S [15].

The data on each parameter were subjected to analysis of variance (ANOVA) using GLM procedure in SAS [16]. For each ANOVA, the least significant difference at $P \le 0.05$ ($LSD_{0.05}$) was used to determine significant differences between treatment means, and standard error of the mean (SEM) and significance are also reported.

3. RESULTS

3.1. Soil Biochemical Properties

At Star City, there was no significant beneficial effect of swine manure or UAN fertilizer application on TOC and TON mass in soil compared to the zero-N control treatment (**Table 3**). At Swift Current, mass of TOC and TON in soil increased with application of swine manure at 3x rate compared to control in the 0 - 7.5 and also in the total 0 - 15 cm depth, with the greatest increase from 3x rate of ADSM applied in spring (**Table 4**). On average, TOC and TON in soil was greater with 3x rate (once in 3 years) than 1x rate (annual application) of swine manure, and greater with ADSM than CTSM in some cases.

At Star City, mass of LFOC and LFON in soil increased with increasing rate of swine manure and also with UAN application compared to the zero-N control treatment in the 0 - 7.5 cm layer (**Table 5**). On average, mass of LFOC and LFON was greater with the 3x rate (once in 3 years) than the 1x rate (annual application) of swine manure in the 0 - 7.5 cm soil layer, but there was little or no effect of timing and type of swine manure application on these parameters. At Swift Current, there was a significant effect of swine manure and N fertilizer treatments on mass of LFOC and LFON in the 0 - 7.5 cm

Table 3. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on mass of total organic C (TOC) and total organic N (TON) in soil in autumn 2008 at Star City, Saskatchewan, Canada (Gray Luvisol soil).

Treatments	TOC mass ($Mg·C·ha^{-1}$) in soil layers (cm)			TON mass ($Mg·N·ha^{-1}$) in soil layers (cm)		
	0 - 7.5	7.5 - 15	0 - 15	0 - 7.5	7.5 - 15	0 - 15
Control	22.27	16.58	38.85	2.024	1.519	3.543
ADSM-3x Autumn	22.57	17.73	40.31	2.037	1.636	3.673
ADSM-1x Autumn	22.26	15.52	37.78	1.999	1.476	3.474
CTSM-3x Autumn	21.86	17.49	39.34	2.082	1.751	3.833
CTSM-1x Autumn	21.31	16.21	37.52	1.926	1.463	3.388
ADSM-3x Spring	22.52	15.99	38.51	2.106	1.588	3.694
ADSM-1x Spring	22.54	17.94	40.48	2.045	1.723	3.768
CTSM-3x Spring	21.96	16.43	38.39	2.001	1.556	3.557
CTSM-1x Spring	21.55	17.90	39.45	1.924	1.673	3.597
UAN Spring	23.64	19.13	42.76	2.106	1.774	3.880
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	0.733^{ns}	1.249^{ns}	1.620^{ns}	0.0731^{ns}	0.1116^{ns}	0.1505^{ns}
Manure rate						
1x	21.91	16.89	38.80	1.973	1.584	3.557
3x	22.23	16.91	39.14	2.057	1.633	3.690
$LSD_{0.05}$	ns	ns	ns	0.112	ns	ns
SEM (Probability)	0.359^{ns}	0.653^{ns}	0.837^{ns}	$0.0385^{\bullet}$	0.0592^{ns}	0.0816^{ns}
Manure type						
ADSM	22.47	16.80	39.27	2.047	1.606	3.653
CTSM	21.67	17.01	38.68	1.983	1.611	3.594
$LSD_{0.05}$	1.04	ns	ns	ns	ns	ns
SEM (Probability)	$0.359^{\bullet}$	0.653^{ns}	0.837^{ns}	0.0385^{ns}	0.0592^{ns}	0.0816^{ns}
Manure application time						
Autumn	22.00	16.74	38.74	2.011	1.581	3.592
Spring	22.14	17.07	39.21	2.019	1.635	3.654
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	0.359^{ns}	0.653^{ns}	0.837^{ns}	0.0385^{ns}	0.0592^{ns}	0.0816^{ns}

$^{\bullet}$ and ^{ns} refer to significant treatment effects in ANOVA at $P \leq 0.10$ and not significant, respectively.

soil layer (**Table 6**). On average, mass of LFOC and LFON in soil was greater with the 3x rate (once in 3 years) than the 1x rate (annual application) of swine manure, but there was little effect of timing and type of swine manure application on these parameters.

At both sites, the correlation coefficients among the TOC, TON, LFOC and LFON fractions in soil were strong, and were highly significant between TOC and TON, and between LFOC and LFON (**Table 7**). At Swift Current, the correlation between TOC and LFOC or LFON was significant at P = 0.12 or 0.15. The correlation coefficients between crop residue C input over 3 growing seasons (**Table 1**) and TOC, TON, LFOC or LFON were not significant in any case at Star City, but

Table 4. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on mass of total organic C (TOC) and total organic N (TON) in soil in autumn 2008 at Swift Current, Saskatchewan, Canada (Dark Brown Chernozem soil).

Treatments	TOC mass ($Mg·C·ha^{-1}$) in soil layers (cm)			TON mass ($Mg·N·ha^{-1}$) in soil layers (cm)		
	0 - 7.5	7.5 - 15	0 - 15	0 - 7.5	7.5 - 15	0 - 15
Control	19.50	15.60	35.10	1.948	1.723	3.671
ADSM-3x Autumn	21.59	16.69	38.28	2.096	1.760	3.856
ADSM-1x Autumn	20.50	17.57	38.07	2.065	1.814	3.879
CTSM-3x Autumn	22.02	15.88	37.90	2.126	1.711	3.837
CTSM-1x Autumn	20.50	16.17	36.67	2.062	1.714	3.776
ADSM-3x Spring	23.31	17.52	40.83	2.347	1.853	4.200
ADSM-1x Spring	20.41	16.17	36.58	2.016	1.694	3.710
CTSM-3x Spring	22.08	16.69	38.77	2.121	1.726	3.847
CTSM-1x Spring	20.67	14.97	35.64	2.084	1.623	3.707
UAN Spring	20.68	16.90	37.58	2.023	1.701	3.724
$LSD_{0.05}$	2.14	ns	3.48	0.178	ns	0.290
SEM (Probability)	0.736^{*}	0.845^{ns}	$1.201^{\bullet}$	0.0613^{*}	0.0682^{ns}	0.0999^{*}
Manure rate						
1x	20.52	16.22	36.74	2.057	1.711	3.768
3x	22.25	16.70	38.95	2.172	1.762	3.935
$LSD_{0.05}$	1.14	ns	1.87	0.107	ns	0.167
SEM (Probability)	0.392^{**}	0.439^{ns}	0.644^{*}	0.0366^{*}	0.0343^{ns}	0.0575^{*}
Manure type						
ADSM	21.45	16.99	38.44	2.131	1.780	3.911
CTSM	21.32	15.93	37.25	2.098	1.693	3.792
$LSD_{0.05}$	ns	1.28	ns	ns	0.100	0.167
SEM (Probability)	0.392^{ns}	$0.439^{\bullet}$	0.644^{ns}	0.0366^{ns}	$0.0343^{\bullet}$	$0.0575^{\bullet}$
Manure application time						
Autumn	21.15	16.58	37.73	2.087	1.750	3.837
Spring	21.62	16.34	37.96	2.142	1.724	3.866
$LSD_{0.05}$	ns	ns	ns	ns	ns	0.167
SEM (Probability)	0.392^{ns}	0.439^{ns}	0.644^{ns}	0.0366^{ns}	0.0343^{ns}	0.0575^{ns}

$^{\bullet}$, *, **and ^{ns} refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$ and not significant, respectively.

was significant for LFOC and LFON at Swift Current. For linear regressions between crop residue C input and TOC, TON, LFOC or LFON, the R^2 values were not significant in any case at Star City, but highly significant for LFOC and LFON at Swift Current (**Table 8**).

3.2. Soil Chemical Properties and Distribution of Available N, P, K and S in the Soil Profile

There was no significant effect of swine manure (frequency, type and application time) or N fertilizer application after three years on soil pH in the 0 - 15 cm layer at either site (data not shown). The soil pH ranged from 6.4 to 6.7 at Star City and from 5.8 to 6.5 at Swift Current among different treatments. There was also no effect of swine manure or N fertilizer treatments on ammonium-N and exchangeable K in soil at both sites, and sulphate-S in soil at Swift Current (data not shown). The amount of nitrate-N increased with the 3x rate of swine manure application in the 30 - 60, 60 - 90 and 90 - 120 cm soil layers at Star City (**Table 9**), and in all soil layers

Table 5. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on mass of light fraction organic C (LFOC) and light fraction organic N (LFON) in soil in autumn 2008 at Star City, Saskatchewan, Canada (Gray Luvisol soil).

Treatments	LFOC mass (Mg·C·ha^{-1}) in soil layers (cm)			LFON mass (Mg·N·ha^{-1}) in soil layers (cm)		
	0 - 7.5	7.5 - 15	0 - 7.5	7.5 - 15	0 - 7.5	7.5 - 15
Control	1931	649	2580	135	35	170
ADSM-3x Autumn	2263	603	2866	158	33	191
ADSM-1x Autumn	2116	749	2865	143	40	183
CTSM-3x Autumn	2286	1004	3290	154	52	206
CTSM-1x Autumn	2306	762	3068	149	41	190
ADSM-3x Spring	2333	817	3150	160	47	207
ADSM-1x Spring	2034	673	2707	134	36	170
CTSM-3x Spring	2277	957	3234	161	55	216
CTSM-1x Spring	1878	875	2753	127	48	175
UAN Spring	2203	952	3155	150	55	205
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	206.8^{ns}	122.1^{ns}	241.7^{ns}	13.3^{ns}	7.2^{ns}	14.6^{ns}
Manure rate						
1x	2083	765	2848	138	41	179
3x	2290	845	3135	158	47	205
$LSD_{0.05}$	296	ns	346	19	ns	21
SEM (Probability)	101.5^{ns}	55.0^{ns}	$118.7^{\bullet}$	6.5^{*}	3.1^{ns}	7.1^{*}
Manure type						
ADSM	2187	710	2897	149	39	188
CTSM	2187	900	3087	148	49	197
$LSD_{0.05}$	ns	160	ns	ns	9	ns
SEM (Probability)	101.5^{ns}	55.0^{*}	118.7^{ns}	6.5^{ns}	3.1^{*}	7.1^{ns}
Manure application time						
Autumn	2242	780	3022	151	41	192
Spring	2131	830	2961	145	47	192
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	101.5^{ns}	55.0^{ns}	118.7^{ns}	6.5^{ns}	3.1^{ns}	7.1^{ns}

$^{\bullet}$, * and ^{ns} refer to significant treatment effects in ANOVA at $P \le 0.10$, $P \le 0.05$ and not significant, respectively.

up to the 120 cm depth at Swift Current (**Table 10**). Application of UAN fertilizer had a significant effect on nitrate-N in soil at Swift Current, but no effect on soil nitrate-N at Star City. The increase in nitrate-N due to swine manure in the 120 cm soil profile was greater with CTSM than ADSM, and also greater with autumn application than spring application at Star City site. However, the opposite was true at Swift Current. The amounts of extractable P in soil tended to increase in a few cases with swine manure application in the 0 - 15 and 15 - 30 cm layers at Star City (**Table 11**) and in the 0 - 15, 15 - 30 or 30 - 60 cm layers at Swift Current (**Table 12**). Application of UAN fertilizer had no significant effect on extractable P in soil at either site. On average, extractable P in soil tended to be greater with CTSM than ADSM at Swift Current, but there was no effect of swine manure

Table 6. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on mass of light fraction organic C (LFOC) and light fraction organic N (LFON) in soil in autumn 2008 at Swift Current, Saskatchewan, Canada (Dark Brown Chernozem soil).

Treatments	LFOC mass ($Mg \cdot C \cdot ha^{-1}$) in soil layers (cm)			LFON mass ($Mg \cdot N \cdot ha^{-1}$) in soil layers (cm)		
	0 - 7.5	7.5 - 15	0 - 7.5	7.5 - 15	0 - 7.5	7.5 - 15
Control	1808	635	2443	123	36	159
ADSM-3x Autumn	2726	806	3532	186	46	231
ADSM-1x Autumn	2360	936	3296	159	53	212
CTSM-3x Autumn	2935	905	3740	201	47	249
CTSM-1x Autumn	2570	884	3454	172	51	223
ADSM-3x Spring	2783	712	3496	190	39	229
ADSM-1x Spring	2272	774	3046	151	43	193
CTSM-3x Spring	2677	777	3454	182	44	225
CTSM-1x Spring	2825	814	3640	189	45	234
UAN Spring	2397	886	3284	163	51	214
$LSD_{0.05}$	679	ns	ns	48	ns	ns
SEM (Probability)	$233.8^{\bullet}$	94.8^{ns}	294.9^{ns}	$16.5^{\bullet}$	5.5^{ns}	19.8^{ns}
Manure rate						
1x	2507	852	3359	167	48	215
3x	2780	775	3555	190	44	234
$LSD_{0.05}$	348	ns	ns	25	ns	ns
SEM (Probability)	$119.4^{\bullet}$	45.4^{ns}	146.3^{ns}	$8.4^{\bullet}$	2.7^{ns}	9.9^{ns}
Manure type						
ADSM	2535	807	3342	171	45	216
CTSM	2752	820	3572	186	47	233
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	119.4^{ns}	45.4^{ns}	146.3^{ns}	8.4^{ns}	2.7^{ns}	9.9^{ns}
Manure application time						
Autumn	2648	857	3505	179	49	228
Spring	2639	769	3408	178	43	221
$LSD_{0.05}$	ns	ns	ns	ns	8	ns
SEM (Probability)	119.4^{ns}	45.4^{ns}	146.3^{ns}	8.4^{ns}	$2.7^{\bullet}$	9.9^{ns}

$^{\bullet}$ and ^{ns} refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

type, rate or application time on extractable P in soil at Star City. At Star City, the amount of sulphate-S in soil increased (but not significantly) with swine manure application mainly in the 30 - 60, 60 - 90 and 90 - 120 cm layers (**Tables 13**). Application of UAN fertilizer had no significant effect on sulphate-S in soil at Star City, and in fact sulphate-S in the surface 0 - 15 cm soil layer tended to decrease compared to the zero-N control treatment. On average, sulphate-S in soil was greater with ADSM than CTSM, considerably greater with autumn application than spring application, and slightly greater with 1x rate than 3x rate of swine manure. There was no effect of any amendment treatment on sulphate-S in soil at Swift Current, and exchangeable K in soil at both sites (data not

Table 7. Relationships among organic C or N fractions (TOC, TON, LFOC, LFON) in the 0 - 15 cm soil, or between crop residue and/or swine manure C input from 2006 to 2008 growing seasons and organic C or N stored in the 0 - 15 cm soil sampled in autumn 2008 at Star City (Gray Luvisol) and Swift Current (Dark Brown Chernozem), Saskatchewan, Canada.

Soil	Parameter	Correlation coefficients (r)			
		TOC	TON	LFOC	LFON
	Relationships among soil organic C or N fractions				
Star City	TOC		0.820^{**}	-0.004^{ns}	0.041^{ns}
	TON			0.279^{ns}	0.276^{ns}
	LFOC				0.950^{***}
	LFON				
Swift Current	TOC		0.913^{***}	$0.492^{\bullet}$	$0.527^{\bullet}$
	TON			0.406^{ns}	0.436^{ns}
	LFOC				0.994^{***}
	LFON				
	Relationships between crop residue and/or swine manure C input and soil organic C or N fractions				
Star City		-0.196^{ns}	-0.083^{ns}	0.413^{ns}	0.226^{ns}
Swift Current		$0.587^{\bullet}$	0.386^{ns}	0.891^{***}	0.921^{***}

$^{\bullet}$, **, *** and ^{ns} refer to significant treatment effects in ANOVA at P ≤ 0.10, P ≤ 0.01, P ≤ 0.001 and not significant, respectively.

Table 8. Linear regressions for relationships between crop residue and swine manure C input from 2006 to 2008 growing seasons and organic C or N (TOC, TON, LFOC, LFON) stored in the 0 - 15 cm soil sampled in autumn 2008 at Star City (Gray Luvisol) and Swift Current (Dark Brown Chernozem), Saskatchewan, Canada.

Soil	Crop parameter (X)	Soil C or N parameter (Y)	[z]Linear regression (Y = a + bX)	R^2
Star City	Crop residue C input	TOC	Y = 40.97 – 0.0002X	0.038^{ns}
		TON	Y = 3.721 – 0.00001X	0.009^{ns}
		LFOC	Y = 2420 + 0.079X	0.170^{ns}
		LFON	Y = 170.5 + 0.003X	0.052^{ns}
Swift Current	Crop residue C input	TOC	Y = 30.21 + 0.001X	0.345^{ns}
		TON	Y = 3.378 + 0.00009X	0.149^{ns}
		LFOC	Y = 848.9 + 0.489X	0.794^{**}
		LFON	Y = 41.41 + 0.035X	0.847^{**}

[z]Y = Soil organic C or N fraction (TOC and TON as Mg C or N·ha^{-1}; and LFOC, LFON as kg C or N·ha^{-1}; a = Intercept on Y, origin of the line; b = Regression coefficient of Y on X, slope of line; X = Crop residue and/or swine manure C input (Mg·ha^{-1}); ** and ^{ns} refer to significant treatment effects in ANOVA at P ≤ 0.01 and not significant, respectively.

shown).

3.3. Amounts of N Uptake in Crop, Nitrate-N in Soil, N Balance Sheets, and Recovery of Applied N

The N balance over the 2006 to 2008 period for the 10 treatments included the amount of nitrate-N recovered in the 0 - 90 cm soil in autumn 2008 and in seed yield (which was removed from the land/field), and N applied as UAN or swine manure, plus N added in seed at seeding over 3 years, and the estimated amount of N balance and unaccounted N (**Tables 14** and **15**). At Star City, the estimated amounts of nitrate-N recovered in soil in autumn 2008 plus N recovered (removed) in seed in 3 years in various treatments ranged from 139 to 357 kg·N·ha^{-1}. The corresponding values of N applied as UAN fertilizer or manure plus N added in seed at seeding in 3 years ranged from 7 to 410 kg·N·ha^{-1}. The amounts of N that

Table 9. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on the amount of residual nitrate-N in soil in autumn 2008 at Star City (Gray Luvisol), Saskatchewan, Canada.

Treatments	Amount of nitrate-N (kg·N·ha^{-1}) in soil layers (cm)					
	0 - 15	15 - 30	30 - 60	60 - 90	90 - 120	0 - 120
Control	6.7	1.2	2.4	4.2	6.2	20.7
ADSM-3x Autumn	5.2	1.4	6.6	14.1	16.6	43.9
ADSM-1x Autumn	5.4	1.7	3.6	7.9	8.2	26.8
CTSM-3x Autumn	5.6	2.0	8.5	37.1	33.8	87.0
CTSM-1x Autumn	3.8	1.5	3.9	7.3	9.0	25.5
ADSM-3x Spring	7.2	1.6	4.8	11.8	13.2	38.6
ADSM-1x Spring	4.9	0.8	1.9	4.5	6.3	18.4
CTSM-3x Spring	5.8	1.3	7.5	25.8	21.2	61.6
CTSM-1x Spring	3.9	1.0	3.6	7.1	8.1	23.7
UAN Spring	4.8	1.1	4.3	7.3	8.3	25.8
$LSD_{0.05}$	ns	0.7	3.9	10.6	7.3	18.8
SEM (Probability)	0.88^{ns}	0.23^{*}	1.35^{*}	3.67^{***}	2.52^{***}	6.49^{***}
Manure rate						
1x	4.5	1.2	3.2	6.7	7.9	23.5
3x	5.9	1.6	6.9	22.2	21.2	57.8
$LSD_{0.05}$	1.3	0.4	2.0	6.8	4.7	12.1
SEM (Probability)	0.43^{*}	$0.13^{\bullet}$	0.69^{**}	2.34^{***}	1.63^{***}	4.16^{***}
Manure type						
ADSM	5.7	1.4	4.2	9.6	11.1	32.0
CTSM	4.8	1.4	5.9	19.3	18.0	49.4
$LSD_{0.05}$	1.3	ns	2.0	6.8	4.7	12.1
SEM (Probability)	$0.43^{\bullet}$	0.13^{ns}	$0.69^{\bullet}$	2.34^{**}	1.63^{**}	4.16^{**}
Manure application time						
Autumn	5.0	1.6	5.6	16.6	16.9	45.7
Spring	5.4	1.2	4.5	12.3	12.2	35.6
$LSD_{0.05}$	ns	0.4	ns	6.8	4.7	12.1
SEM (Probability)	0.43^{ns}	0.13*	0.69^{ns}	2.34^{ns}	1.63^{*}	$4.16^{\bullet}$

$^{\bullet}$, *, **, *** and ^{ns} refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

could not be accounted for ranged from −132 to 57 kg·N·ha^{-1}. The amounts of unaccounted N from N applied/added ranged from 91 to 192 kg·N·ha^{-1}. At Swift Current, the estimated amounts of nitrate-N recovered in soil in autumn 2008 plus N recovered (removed) in seed in 3 years in various treatments ranged from 170 to 399 kg·N·ha^{-1}. The corresponding values of N applied as UAN fertilizer or manure plus N added in seed at seeding in 3 years ranged from 7 to 410 kg·N·ha^{-1}. The amounts of N that could not be accounted for ranged from −163 to 101 kg·N·ha^{-1}. The amounts of unaccounted N from N applied/added ranged from 35 to 207 kg·N·ha^{-1}. The percent recovery of applied N over 3 years ranged from 37.7% to 50.0% in seed and from 50.7% to 65.0% in seed + straw at Star City, and from 0.3% to 7.0% in seed and from 27.5 to 54.7 in seed + straw at

Table 10. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on the amount of residual nitrate-N in soil in autumn 2008 at Swift Current (Dark Brown Chernozem), Saskatchewan, Canada.

Treatments	Amount of nitrate-N ($kg \cdot N \cdot ha^{-1}$) in soil layers (cm)					
	0 - 15	15 - 30	30 - 60	60 - 90	90 - 120	0 - 120
Control	5.9	2.0	2.9	12.8	37.5	61.1
ADSM-3x Autumn	10.3	7.8	29.9	85.9	46.6	180.5
ADSM-1x Autumn	14.8	9.8	53.6	43.1	43.0	164.3
CTSM-3x Autumn	11.4	6.6	63.8	79.1	30.0	190.9
CTSM-1x Autumn	13.8	13.7	121.7	61.4	41.1	251.7
ADSM-3x Spring	12.5	8.5	45.8	122.1	83.5	272.4
ADSM-1x Spring	11.8	10.1	50.1	41.6	22.8	136.4
CTSM-3x Spring	13.5	5.7	69.2	89.5	46.0	223.9
CTSM-1x Spring	17.8	16.7	53.9	48.0	43.2	179.6
UAN Spring	10.0	7.1	22.5	68.0	63.8	171.4
$LSD_{0.05}$	5.7	7.4	56.1	45.5	31.2	91.4
SEM (Probability)	1.98^{*}	2.56^{*}	19.33^{*}	15.69^{**}	10.77^{*}	31.51^{**}
Manure rate						
1x	14.6	12.6	69.8	48.5	37.5	183.0
3x	11.9	7.1	52.2	94.1	51.5	216.8
$LSD_{0.05}$	3.0	4.1	ns	24.2	18.0	ns
SEM (Probability)	$1.03^{\bullet}$	1.41^{*}	11.02^{ns}	8.30^{***}	$6.19^{\bullet}$	18.69^{ns}
Manure type						
ADSM	12.3	9.0	44.9	73.2	49.0	188.4
CTSM	14.1	10.7	77.2	69.5	40.1	211.6
$LSD_{0.05}$	ns	ns	32.1	ns	ns	ns
SEM (Probability)	1.03^{ns}	1.41^{ns}	11.02*	8.30^{ns}	6.19^{ns}	18.69^{ns}
Manure application time						
Autumn	12.6	9.4	67.3	67.4	40.2	196.9
Spring	13.9	10.2	54.8	75.3	48.9	203.1
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	1.03^{ns}	1.41^{ns}	11.02^{ns}	8.30^{ns}	6.19^{ns}	18.69^{ns}

$^{\bullet}$, *, **, *** and ^{ns} refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Swift Current in the various swine manure or N fertilizer treatments (**Tables 14** and **15**). The recovery of applied N in seed or seed + straw for swine manure was usually greater in the 3x than the 1x rate and also greater with the ADSM than the CTSM treatments.

4. DISCUSSION

Research has shown potential for improvement in organic C and/or N storage in soil and/or increase in soil fertility level from the application of LSM [1,5,6] and N fertilization [17-19]. Previous research has also suggested that long-term application of LSM can increase N, P, S and K fertility of soil, due to the return of these nutrients in manure and in crop residue to soil over years [1]. Similarly, in our study, applications of LSM and N fertilizer increased organic C and N, and amounts of

Table 11. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on the amount of residual extractable P in soil in autumn 2008 at Star City (Gray Luvisol), Saskatchewan, Canada.

Treatments	Amount of extractable P ($kg \cdot N \cdot ha^{-1}$) in soil layers (cm)					
	0 - 15	15 - 30	30 - 60	60 - 90	90 - 120	0 - 120
Control	21.4	8.6	12.6	6.0	4.5	53.1
ADSM-3x Autumn	22.0	11.5	7.1	5.7	4.3	50.6
ADSM-1x Autumn	21.7	10.5	9.1	3.9	3.3	48.5
CTSM-3x Autumn	18.4	8.6	10.9	3.3	3.6	44.8
CTSM-1x Autumn	27.2	11.9	7.4	4.7	5.0	56.2
ADSM-3x Spring	18.4	9.1	10.3	5.5	4.2	47.5
ADSM-1x Spring	34.2	16.8	8.7	4.8	4.1	68.6
CTSM-3x Spring	39.3	11.2	12.7	6.4	4.2	73.8
CTSM-1x Spring	24.0	9.8	10.8	5.0	7.5	57.1
UAN Spring	21.8	10.0	9.4	4.8	5.2	51.2
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	5.88^{ns}	2.29^{ns}	3.42^{ns}	1.06^{ns}	1.43^{ns}	8.28^{ns}
Manure rate						
1x	26.8	12.3	9.0	4.6	5.0	57.5
3x	24.5	10.1	10.3	5.2	4.1	54.2
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	3.24^{ns}	1.21^{ns}	1.73^{ns}	0.53^{ns}	0.76^{ns}	4.39^{ns}
Manure type						
ADSM	24.1	12.0	8.8	5.0	4.0	53.9
CTSM	27.2	10.4	10.5	4.9	5.1	58.1
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	3.24^{ns}	1.21^{ns}	1.73^{ns}	0.53^{ns}	0.76^{ns}	4.39^{ns}
Manure application time						
Autumn	22.3	10.6	8.6	4.4	4.1	50.0
Spring	29.0	11.7	10.6	5.4	5.0	61.7
$LSD_{0.05}$	ns	ns	ns	ns	ns	12.8
SEM (Probability)	3.24^{ns}	1.21^{ns}	1.73^{ns}	0.53^{ns}	0.76^{ns}	$4.39^{\bullet}$

$^{\bullet}$ and ^{ns} refer to significant treatment effects in ANOVA at $P \leq 0.10$ and not significant, respectively.

plant-available N, P or S in soil in many cases, depending on soil type/site. The following sections discuss the short-term effects of LSM and N fertilization on soil biochemical and chemical properties.

4.1. Soil Biochemical Properties

Earlier research has shown positive effects of swine manure or N fertilizer application on crop yield, and soil organic matter and fertility [1,5,6]. Similarly, we found increase in TOC and TON from swine manure application due to its dual effect by directly contributing to organic C and N, plus additional indirect contribution of C from increased crop residue (roots, stubble, straw, chaff/fallen leaves) returned to the land/soil, as evidenced by greatest increase in straw yield in this treatment [7]. Inorganic fertilizers supply specific nutrients, but do not

Table 12. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on the amount of residual extractable P in soil in autumn 2008 at Swift Current (Dark Brown Chernozem), Saskatchewan, Canada.

Treatments	Amount of extractable P ($kg \cdot P \cdot ha^{-1}$) in soil layers (cm)					
	0 - 15	15 - 30	30 - 60	60 - 90	90 - 120	0 - 120
Control	53.0	8.4	7.7	7.3	13.4	89.7
ADSM-3x Autumn	55.0	9.1	8.7	8.2	13.9	94.9
ADSM-1x Autumn	51.6	8.4	11.0	8.0	19.6	98.6
CTSM-3x Autumn	48.4	8.1	6.9	7.3	25.9	96.6
CTSM-1x Autumn	56.8	10.6	7.1	9.1	24.7	108.3
ADSM-3x Spring	48.1	11.0	11.6	5.4	16.6	92.7
ADSM-1x Spring	52.4	8.4	8.5	4.6	16.7	90.6
CTSM-3x Spring	66.6	13.7	8.1	6.1	15.7	110.2
CTSM-1x Spring	59.6	8.6	7.2	6.2	18.4	100.0
UAN Spring	54.3	10.4	9.1	5.3	14.6	93.7
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	7.25^{ns}	2.01^{ns}	1.68^{ns}	1.80^{ns}	3.33^{ns}	8.64^{ns}
Manure rate						
1x	55.1	9.0	8.5	7.0	19.8	99.4
3x	54.5	10.5	8.8	6.8	18.0	98.6
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	3.71^{ns}	1.02^{ns}	0.83^{ns}	0.87^{ns}	1.77^{ns}	4.06^{ns}
Manure type						
ADSM	51.8	9.2	10.0	6.5	16.7	94.2
CTSM	57.9	10.3	7.4	7.2	21.2	104.0
$LSD_{0.05}$	ns	ns	2.4	ns	5.2	11.8
SEM (Probability)	3.71^{ns}	1.02^{ns}	0.83*	0.87^{ns}	1.77$^{\bullet}$	4.06$^{\bullet}$
Manure application time						
Autumn	53.0	9.1	8.4	8.2	21.0	99.7
Spring	56.7	10.5	8.9	5.6	16.8	98.5
$LSD_{0.05}$	ns	ns	ns	2.5	5.2	ns
SEM (Probability)	3.71^{ns}	1.02^{ns}	0.83^{ns}	0.87*	1.77$^{\bullet}$	4.06^{ns}

$^{\bullet}$, * and ^{ns} refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$ and not significant, respectively.

contribute directly to soil organic matter, and thus may result in much less contribution to soil organic C and N. However, in our study, there was relatively greater storage of organic C and N from N fertilizer application than swine manure, at least at Star City site. The smaller storage of TOC or TON from swine manure or UAN fertilizer applications at Star City than Swift Current was probably due to the differences in soil type (Gray Luvisol loam soil at Star City versus Brown Chernozem silt loam at Swift Current) and climatic conditions (relatively moister soils at Star City than Swift Current) at the two sites, resulting in greater turn over of organic matter at Star City compared to Swift Current.

In our study, the changes in LFOC and LFON due to LSM application and N fertilization were more pronounced than TOC and TON in both soils. For example,

Table 13. Effect of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 on the amount of residual sulphate-S in soil in autumn 2008 at Star City (Gray Luvisol), Saskatchewan, Canada.

Treatments	Amount of sulphate-S ($kg \cdot S \cdot ha^{-1}$) in soil layers (cm)					
	0 - 15	15 - 30	30 - 60	60 - 90	90 - 120	0 - 120
Control	27.9	8.8	12.7	11.2	13.8	74.4
ADSM-3x Autumn	23.3	9.7	20.5	44.5	45.1	143.1
ADSM-1x Autumn	27.8	10.4	13.2	19.0	30.1	100.5
CTSM-3x Autumn	18.9	10.1	13.4	10.7	9.9	63.0
CTSM-1x Autumn	22.7	11.1	16.5	38.2	42.6	131.1
ADSM-3x Spring	30.2	10.1	11.6	12.1	11.2	75.2
ADSM-1x Spring	25.8	9.1	10.4	9.5	8.8	63.6
CTSM-3x Spring	18.1	9.8	13.2	9.5	8.6	59.4
CTSM-1x Spring	17.0	8.1	12.7	13.9	22.2	73.9
UAN Spring	18.6	10.3	12.0	12.4	13.7	67.0
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	6.48^{ns}	0.99^{ns}	4.24^{ns}	12.68^{ns}	11.77^{ns}	28.29^{ns}
Manure rate						
1x	23.3	9.7	13.2	20.1	25.9	92.2
3x	22.7	9.9	14.7	19.2	18.8	85.3
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
SEM (Probability)	3.15^{ns}	0.51^{ns}	2.23^{ns}	7.04^{ns}	6.62^{ns}	15.42^{ns}
Manure type						
ADSM	26.8	9.8	13.9	21.3	23.8	95.6
CTSM	19.2	9.8	13.9	18.1	20.9	81.9
$LSD_{0.05}$	9.2	ns	ns	ns	ns	ns
SEM (Probability)	$3.15^{\bullet}$	0.51^{ns}	2.23^{ns}	7.04^{ns}	6.62^{ns}	15.42^{ns}
Manure application time						
Autumn	23.2	10.3	15.9	28.1	31.9	109.4
Spring	22.8	9.3	12.0	11.2	12.8	68.1
$LSD_{0.05}$	ns	ns	ns	20.5	19.3	44.9
SEM (Probability)	3.15^{ns}	0.51^{ns}	2.23^{ns}	$7.04^{\bullet}$	6.62^{*}	$15.42^{\bullet}$

$^{\bullet}$, * and ^{ns} refer to significant treatment effects in ANOVA at $P \le 0.10$, $P \le 0.05$ and not significant, respectively.

in the 0 - 15 cm soil layer after 3 years, and compared to the zero-N control treatment, the manure and N fertilizer treatments, respectively, increased TOC by 10.1% and 3.2%, TON by 9.5% and 2.3%, LFOC by 22.3% and 16.0% and LFON by 20.6% and 12.9% at Star City. The corresponding increases at Swift Current were 7.1% and 7.8% for TOC, 1.4% and 4.9% for TON, 34.4% and 41.5% for LFOC and 34.6% and 41.5% for LFON, respectively. Other researchers have also observed greater responses of LFOC and LFON to N fertilization and other management practices than TOC and TON [18-20]. Our findings confirm that the changes in LFOC and LFON can be considered good indicators of changes of organic C and N in soil as a result of manure addition or appropriate fertilization. This also suggests that monitoring the changes in LFON and LFOC in the surface soil

Table 14. Balance sheets of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 at Star City (Gray Luvisol), Saskatchewan, Canada.

Parameters	Treatments									
	Control	UAN spring	Fall application				Spring application			
			ADSM-3x	ADSM-1x	CTSM-3x	CTSM-1x	ADSM-3x	ADSM-1x	CTSM-3x	CTSM-1x
Nitrate-N recovered in soil (0 - 90 cm) after 3 years in fall 2008 (kg·N·ha^{-1})	21	26	44	27	87	26	39	18	62	24
N recovered in seed in 3 years kg·N·ha^{-1})	118	199	225	204	270	284	235	242	253	262
N recovered in soil after 3 years + N recovered in seed in 3 years (kg·N·ha^{-1})	139	225	269	231	357	310	274	260	315	286
Total N applied in UAN or in SM in 3 years (kg·N·ha^{-1})	0	180	214	205	403	360	257	255	343	326
Organic N added in seed in 3 years (kg·N·ha^{-1})	7	7	7	7	7	7	7	7	7	7
Total N added in UAN + SM + seed in 3 years (kg·N·ha^{-1})	7	187	221	212	410	367	264	262	350	333
N balance (N applied in UAN/SM/seed – N recovered in seed) (kg·N·ha^{-1})	−111	−12	−4	8	140	83	29	20	97	71
Unaccounted N (N applied in UAN/SM/seed – N recovered in soil + seed) (kg·N·ha^{-1})	−132	−38	−48	−19	53	57	−10	2	35	47
N recovered in seed in 3 years from applied N (kg·N·ha^{-1})		81	107	86	152	166	117	124	135	144
N recovered in soil after years + seed in 3 years from applied N (kg·N·ha^{-1})		86	130	92	218	171	134	121	176	147
N balance (N applied in UAN/SM/seed – N recovered in seed from applied N) (kg·N·ha^{-1})		106	114	126	258	201	147	138	215	189
Unaccounted N (N applied in UAN/SM/seed – N recovered in soil + seed from applied N) (kg·N·ha^{-1})		101	91	120	192	196	130	141	174	186
Recovery of applied N in seed over 3 years (%)		45.0	50.0	42.0	37.7	46.1	45.5	48.6	39.4	44.2
N recovered in seed + straw in 3 years (kg·N·ha^{-1})	159	264	298	263	365	371	313	311	346	341
Recovery of applied N in seed + straw over 3 years (%)		58.3	65.0	50.7	51.1	58.9	59.9	59.6	54.5	55.8

could be a good strategy to determine the potential for N supplying power, and improvement in soil quality/health. The trends of higher organic C and N in light organic fractions than total organic fractions in the manure and N fertilizer treatments were most likely associated with greater inputs of C and N to soil through manure, and also straw, chaff [17] and roots [21,22].

The relative greater increases in C or N for LFOC or LFON than TOC or TON in our study are in agreement with other research, where light organic fraction was also more responsive to management practices than total organic fraction [18-20]. Unlike TOC and TON, there was a greater build-up of light fraction organic C or N at Swift Current than at Star City, in spite of greater input of C from crop residues plus LSM in 3 years at Star City than Swift Current. We do not have any real explanation for this unusual trend for the greater build-up of light organic fraction under relatively warmer temperature conditions at Swift Current than Star City, but this may be possibly due to relatively drier conditions which may have resulted in relatively slower decomposition of freshly added crop residues at swift Current than Star City.

Earlier long-term research studies have shown strong and highly significant correlations among TOC, TON, LFOC and LFON fractions in soil due to management practices [18-20]. However, in our study, the strong positive correlations were found only between TOC and TON,

Table 15. Balance sheets of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and urea-ammonium-nitrate (UAN) solution fertilizer over three years from 2006 to 2008 at Swift Current (Dark Brown Chernozem), Saskatchewan, Canada.

Parameters	Treatments									
	Control	UAN spring	Fall application				Spring application			
			ADSM-3x	ADSM-1x	CTSM-3x	CTSM-1x	ADSM-3x	ADSM-1x	CTSM-3x	CTSM-1x
Nitrate-N recovered in soil (0 - 90 cm) after 3 years in autumn 2008 ($kg·N·ha^{-1}$)	61	171	181	164	191	252	272	136	224	180
N recovered in seed in 3 years ($kg·N·ha^{-1}$)	109	110	123	114	118	110	127	112	132	116
N recovered in soil after 3 years + N recovered in seed in 3 years $kg·N·ha^{-1}$)	170	281	304	278	309	362	399	248	356	296
Total N applied in UAN or in SM in 3 years ($kg·N·ha^{-1}$)	0	180	214	205	403	360	257	255	343	326
Organic N added in seed in 3 years ($kg·N·ha^{-1}$)	7	7	7	7	7	7	7	7	7	7
Total N added in UAN + SM + seed in 3 years ($kg·N·ha^{-1}$)	7	187	221	212	410	367	264	262	350	333
N balance (N applied in UAN/SM/seed – N recovered in seed) ($kg·N·ha^{-1}$)	−102	77	98	98	292	257	137	150	218	217
Unaccounted N (N applied in UAN/SM/seed – N recovered in soil + seed) ($kg·N·ha^{-1}$)	−163	−94	−83	−66	101	5	−135	14	−6	37
N recovered in seed in 3 years from applied N $kg·N·ha^{-1}$)		1	14	5	9	1	18	3	23	7
N recovered in soil after years + seed in 3 years from applied N ($kg·N·ha^{-1}$)		111	134	108	139	192	229	78	186	126
N balance (N applied in UAN/SM/ seed – N recovered in seed from applied N) ($kg·N·ha^{-1}$)		186	207	207	401	366	249	259	327	326
Unaccounted N (N applied in UAN/SM/seed – N recovered in soil + seed from applied N) ($kg·N·ha^{-1}$)		76	87	104	271	175	35	184	164	207
Recovery of applied N in seed over 3 years (%)		0.6	6.5	2.4	2.2	0.3	7.0	1.2	6.7	2.1
N recovered in seed + straw in 3 years ($kg·N·ha^{-1}$)	162	242	279	240	297	261	290	233	299	259
Recovery of applied N in seed + straw over 3 years (%)		44.4	54.7	38.0	35.5	27.5	49.8	27.8	39.9	29.8

and between LFOC and LFON in both soils. Previous long-term studies have shown positive relationships between the input of increased amounts of manure and/or crop residue C or N and TOC, TON, LFOC or LFON, especially in the labile/light organic fractions [18-20, 23,24]. However, in our study after 3 years, the significant linear regressions between the amounts of C or N input and mass of organic C or N in the 0 - 15 cm soil layer in various organic fractions were found only for LFOC and LFON and only at Swift Current. This lack of significant relationships between C or N input and mass of organic C or N stored in soil was probably due to short duration of our study.

4.2. Soil Chemical Properties and Distribution of Available N, P, K and S in the Soil Profile

Slow acidification of soil from N fertilization has been earlier reported after long-term annual applications of moderate rates of N fertilizer to annual crops in North America [25-27]. However, in our study, there was no effect of manure or N fertilization on soil pH, and this was probably due to the shorter duration of our present study. In a study in Quebec, Canada, Ndayegamiye and Cote [5] also found no effect of pig slurry application on soil pH even after 10 annual applications.

There was no build-up of residual ammonium-N in soil after three annual applications of swine manure or N fertilizer, no doubt due to the rapid nitrification of any ammonium-N released during mineralization of organic matter. The amount of residual nitrate-N in soil increased with increasing rate of swine manure in the 30 - 60, 60 - 90 and 90 - 120 cm layers in the 0 - 120 cm soil profile, particularly at Swift Current. This suggests potential risk of nitrate leaching below the root zone, even within the short duration of our study (only three years), as other long-term studies in China have shown a great potential of underground water contamination with nitrate-N from annual applications of farmyard manure (FYM) at relatively high rates [28-30]. Our findings also suggest the need for deep soil sampling, as soils in our study were sampled only to the 120 cm depth. In our study at Star City, there was a significant increase in nitrate-N in the soil profile with 3x LSM rate while there was only little increase in residual nitrate-N in the 0 - 120 cm soil profile due to fertilizer N application. The rate of fertilizer-N applied in our study was below the rate needed for optimum yield in this soil-climatic region [31], and the amount of N removed in the grain closely matched the amount of fertilizer-N added. This would have minimized the amount of surplus N available for leaching or other losses. However, a portion of the applied N may have been immobilized into the soil organic N pool, especially when straw was retained [20]. It is also possible that a portion of the residual soil nitrate-N may have been lost as gaseous N over the winter and especially in early spring after snow melting [32,33]. It is unlikely that much of the applied N at Star City leached below the 120 cm depth, as evidenced by little residual nitrate-N recovered in the 30 - 60, 60 - 90 and 90 - 120 cm soil layers in autumn 2008 sampling

At Swift Current, the amounts of fertilizer and manure N applied exceeded the amounts of N removed in the grain, and based on the moderate amounts of residual nitrate-N recovered in the 30 - 60, 60 - 90 and 90 - 120 cm soil layers in autumn 2008 at Swift Current it may well that a portion of the applied N had leached below the 120 cm depth, particularly at the high rate of manure. Previous research in Saskatchewan where soil samples were taken to 240 cm depth after 12 growing seasons, Malhi *et al.* [34] observed large amounts of residual nitrate-N accumulation in the 210 - 240 cm layer for treatments where N applications had exceeded N removals. It should be noted that at Swift Current, crops were drought stressed during grain filling during both 2006 and 2007 and final grain yields were greatly depressed, while in 2008 the study suffered severe hail damage prior to grain filling. Minimal grain N uptake at Swift Current in all three years no doubt influenced the amount of nitrate N accumulating in the soil profile. Regardless, the results also emphasizes the need for deep soil sampling (maybe up to 3 or 4 m depth) in future research in order to make valid conclusions related to nitrate leaching losses in the soil profile.

Earlier research in China has shown substantial increase in extractable P and total P in soil with long-term annual applications of FYM [35]. In our study, there was a tendency towards increased extractable P in the surface 0 - 5 cm soil with swine manure in some treatments even after three annual applications, probably due to fairly high concentration of P in swine manure. The increase of extractable P with swine manure only in the 0 - 15 cm soil layer suggests that P is relatively immobile, but the slow build-up of P in the surface soil, especially after repeated applications to increase crop production, may subsequently increase the potential risk of contamination of surface waters with P from surface run-off of water after snow melt in early spring and/or after heavy rainfall events which often occur in this region during summer.

Sulphate-S in soil tended to increase with swine manure at Star City. This suggests that swine manure either contained sulphate-S or possibly increased sulphate-S through mineralization of organic matter. Sulphate-S increased with increasing rate of swine manure. It is possible that a portion of the sulphate-S may have leached below the 120 cm depth, as evidenced by large amounts of sulphate-S in the 30 - 60, 60 - 90 and 90 - 120 cm layers, although no soil samples were obtained below 120 cm to verify this in our study. This suggests the need for future soil sampling to greater depths in order to make valid conclusions related to sulphate-S leaching. Earlier research in Saskatchewan has suggested that long-term application of LSM can increase K fertility of soil, due to the return of these nutrients in manure and in crop residue to soil over years [1]. However, in our present study, there was no increase in extractable K in soil from LSM or UAN application over three years at both sites.

4.3. Amounts of N Uptake in Crop, Nitrate-N in Soil, N Balance Sheets, and Recovery of Applied N

The amounts of unaccounted N increased with application of swine manure or N fertilizer compared to zero-N control. This unaccounted N reflects a portion of the applied N which did not become available to the crop, and may have been lost from the soil mineral N pool and/or from the soil-plant system. At Star City, it is unlikely that a portion of the applied N was leached down below 120 cm soil depth, because there was little nitrate-N recovered in the deeper soil layers in autumn 2008. At Swift Current, it is possible that a portion of the applied N may have leached down below 120 cm soil depth, because there were large amounts of nitrate-N recovered in the 30 - 60, 60 - 90 and 90 - 120 cm soil layers in autumn 2008 in many cases for swine manure and UAN treatments. Other researchers have reported an increase in the concentration of residual nitrate-N in the soil profile at high N fertilizer rates [36-39], and any soil nitrate-N below the effective root zone of crops is susceptible to leaching, The loss of nitrate-N through leaching can result in N contamination of groundwater, and thus represents a potential risk to groundwater quality and soil health [40]. Our N balance results suggest that a portion of the applied N in the N treatments may have been immobilized in soil organic N, as evidenced by higher amount of soil organic N, especially in LFON even after 3 years in autumn 2008 (**Tables 3-6**). At Star City, the amount of applied N recovered in LFON in soil ranged from −155 to 290 $kg \cdot N \cdot ha^{-1}$ in various swine manure and UAN treatments. The corresponding values for the amounts of applied N recovered in total organic N in soil at Swift Current ranged from 36 to 529 $kg \cdot N \cdot ha^{-1}$. In addition, it is possible that a portion of the applied N may have been lost from the soil-plant system through denitrification (e.g., nitrous oxide and other N gases) due to wet surface soil conditions which temporarily exist in the present study area in most years in early spring after snow melt, or after occasional heavy rainfalls during summer and/or autumn [32,33,41]. It is also possible that a small portion of the applied N may have leached below the 120 cm soil depth profile, as suggested by Malhi *et al.* [34] who found large amounts of nitrate-N accumulation in the 120 to 240 cm soil profile in a long-term study in Saskatchewan with high input of N fertilizer and low crop intensity. This suggests the need for deep soil sampling below the 120 cm depth in future in our present long-term experiments.

Overall, the amount of residual soil nitrate-N recovered in the 0 - 120 cm soil profile was relatively small in the Gray Luvisol soil at Star City. This indicates low accumulation of nitrate-N in the soil profile. However, large amounts of unaccounted N from applied N suggest a great potential for gaseous N loss, especially in early spring after snow thawing when the surface soil is very wet (conducive to denitrification), and N immobilization, and possibility of some nitrate-N leaching below the 120 cm depth soil profile in the Brown Chernozem soil at Swift Current. However, as noted previously, grain N uptake was limited due to environmental conditions which no doubt influenced the amount of nitrate N accumulating in the soil profile. There were large amounts of N balance and unaccounted N in the zero-N treatments and also in the swine manure or N fertilizer treatments, especially at Swift Current. The implication of these large negative values for N balance and unaccounted N in the zero-N treatments is that large amounts of N became available to the crops in the growing seasons through mineralization of soil organic matter. However, the large negative values for N balance and unaccounted N in the N fertilizer treatments at Swift Current suggest that the soil at this site may be gaining some N by wet/dry deposition through precipitation (rain/snow) and possibly by non-symbiotic N fixation. The Swift Current site is not close to any large city or industry, we don't know if soil at this site gained any N deposited through dry (snow) and wet (rainfall) precipitation. This supports the need for future research to obtain information on the contribution of N from rain/snow and non-symbiotic N fixation, or other outside sources, in order to optimize the use and accounting of N resources, and their effects on greenhouse gas (GHG) emissions to the atmosphere.

The percent recovery of applied N over 3 years ranged from 37.7% to 50.0% in seed and from 50.7% to 65.0% in seed + straw at Star City, and from 0.3% to 7.0% in seed and from 27.5 to 54.7 in seed + straw at Swift Current in various swine manure or N fertilizer treatments (**Tables 13** and **14**). The recovery of applied N in seed or seed + straw for swine manure was usually greater in the 3x rate than the 1x rate and also greater with the ADSM than the CTSM treatments. The greater recovery of applied N from swine manure in seed or seed + straw with the 3x rate than the 1x rate was possibly due to greater mineralization of any organic N because of much longer time of contact with soil microorganisms. The poor recovery of applied N in LSM or UAN fertilizer at Swift Current was most likely due to lack of crop response to these amendments, thus low input of organic C or N from crop residue which probably is the main/major source of C or N input to soil.

5. CONCLUSION

Our findings suggest that the quantity and quality of organic C and N in soil can be affected by swine manure rate and type, and N fertilization, most likely influencing inputs of C and N through crop residue, and improve soil quality.

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